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Progress in Infrared Pyrometry Measurements of Shocked Solids

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Introduction

Temperature measurement is one of the grand challenges still facing experimental shock physics. A shock experiment fundamentally measures $E(\sigma_x, \varepsilon_{11})$ which is an incomplete equation of state since temperature (or entropy) remains unspecified. Ideally, one would like to experimentally determine a free energy $F(T, \varepsilon_{ij})$ from which all other thermo-mechanical properties might be derived. In practice, temperature measurement would allow direct comparison with theory/simulation since T and ε_{11} are in most theories the underlying variables. Temperature is a sensitive measure of energy partitioning, knowledge of which would increase our understanding phase boundaries and thermally activated processes (such as chemical reactivity (including dissociation and ionization)). Temperature measurement would also allow a thermodynamically consistent coupling of hydrodynamic equations of state to the material s constitutive (deformation) behavior.

The measurement of the temperature of a material that has undergone severe strains at small time-scales is extremely difficult, and we are developing a method using infrared reflectance and pyrometry. The emitted power from a warm surface is measured over a range of wavelengths using a multi-channel IR detector with a response time of ~0.1μs. Each channel of the detector passes the radiation from a selected wavelength interval into a detector. Pyrometers typically have anywhere from three to six channels, and not all channels may have enough signal to contribute to the measurement under any given condition. The difficulty in the measurement lies in relating the radiance (power per unit area per solid angle) in each channel to the temperature of the surface since the radiance is determined not only by the temperature, but also by the emissivity of the surface. The emissivity is not a constant for any real surface, but varies both with angle of observation and with wavelength. Thus the temperature cannot be calculated from the emitted radiance spectrum without detailed knowledge of the emissivity. Approximate temperatures may be calculated by various assumptions, such as assuming a fixed number for the emissivity (greybody), assuming the emissivity in adjacent channels is the same (the relative emissivity then drops out of the relations governing the power ratio), and by assuming a lower limit on the emissivity which yields a range of temperatures and emissivities in each channel consistent with the measurement. We hope to show that the emissivity in each wavelength channel and the temperature can be uniquely determined if in addition to measuring the emitted power we also measure the power of the reflected light from a fast (sub μs) light source of known spectral content. In addition, it is not necessary to know the absolute values of the flux, either reflected or emitted. This is a great advantage because the exact geometry of the configuration may be rapidly changing or not known at all.

The results of a tabletop experiment designed to demonstrate the method and initial gas gun experiments will be discussed. The goal of the tabletop experiment was to show that the temperature measurement can be accomplished in less than one s (time length of steady state behavior [1]). We have previously shown that the emitted signals can be acquired in approximately 0.2 s [1]. We demonstrate that we can create and measure an additional signal from an exterior light source in less than a microsecond which allows the determination of the temperature and emissivity of a heated surface.

Theory

Each channel (i) detects emitted (S) and reflected (R) light from the surface with:

$$S_i = \varepsilon_i F_i(T) K C_i \qquad\qquad R_i = (1 - \varepsilon_i) I_i H C_i.$$

We assume that the reflectivity is unity minus the emissivity for each wavelength. H and K are geometry factors assumed to be independent of the wavelength. C is the sensor calibration factor, F(T) is the black body radiance, I is the power from the flash lamp, and ε is the emissivity of surface.

The use of relative values, i.e. the spectrum instead of absolute flux, eliminates serious problems with absolute calibration and the instantaneous measurement of geometry. Hence we choose an arbitrary channel "n" (typically the one with the largest emitted signal) and normalize the equations giving:

$$A_i = S_iC_n/S_nC_i = (\varepsilon_i / \varepsilon_n)(F_i / F_n) = e_i B_i(T)$$

$$D_i = R_iC_n/R_nC_i = (I_i/I_n)(1 - (\varepsilon_i / \varepsilon_n)\varepsilon_n)/(1 - \varepsilon_n) = E_i(1 - e_i \varepsilon_n)/(1 - \varepsilon_n).$$

We know the values of A_i, D_i, and E_i, and the functional dependence of B_i on T. This set of equations allows the solution of e_i, ε_n, and T. Every set of three channels yield a temperature and a set of emissivities if the reflectivity relations are used. When the relative emissivities are close to unity (the greybody case), the reflectivity relations contribute no information, and any two of the channels yield a temperature. The spread of calculated temperatures is a measure of the consistency and accuracy of the data. An alternative approach is to take a material of known reflectivity (i.e. gold with a reflectivity of near unity) and compare the reflected powers to backout the emissivities of the material in question. When the emissivities are very small so that the reflectivities are near unity, but the ratios of the emissivities in pairwise channels differ greatly from unity there is a serious problem that can only be solved by extreme accuracy in the data. It should also be noted that the equation set above has no constraints, i.e. there is nothing in the equations that force the emissivities to be positive and less than unity.

To try to get around the issue of the angular dependence of emissivity, the reflectivity and emissivity should be integrated over all angles; this can be accomplished experimentally by enclosing the hot surface by a fully reflecting surface. This also enhances the signal.

Tabletop Experiment

Photographs of the equipment are shown in Figs. 1 and 2. The hot surface used for the experiment was a Mo disk heated by a commercially available single-sided 400 W HSP-31 3.25" D disk heater from Chromalox (Division of Emerson Electric). We powered it with AC current from a Variac. The external source of light was a high pressure Xe lamp with a sapphire window from Hamamatsu able to pulse in the sub-microsecond range with light output from the UV to the 5μm range. The pulse as detected by one of the IR channels is shown in Fig. 3. The detector has six channels, each selected for a particular wavelength region. Each channel has an IR detector, optics, a bandpass filter, and passes the light from the surface to the detector via infrared transmitting optical fibers. It is similar to the detector described in Ref. 1.

The intent of this experiment was to demonstrate the use of the fast reflection measurement and analysis. Since it is difficult to maintain a highly reflecting surface in the presence of a continuous source of heat, this experiment does not use a reflecting enclosure to integrate the emissivities and reflectivities over all angles.

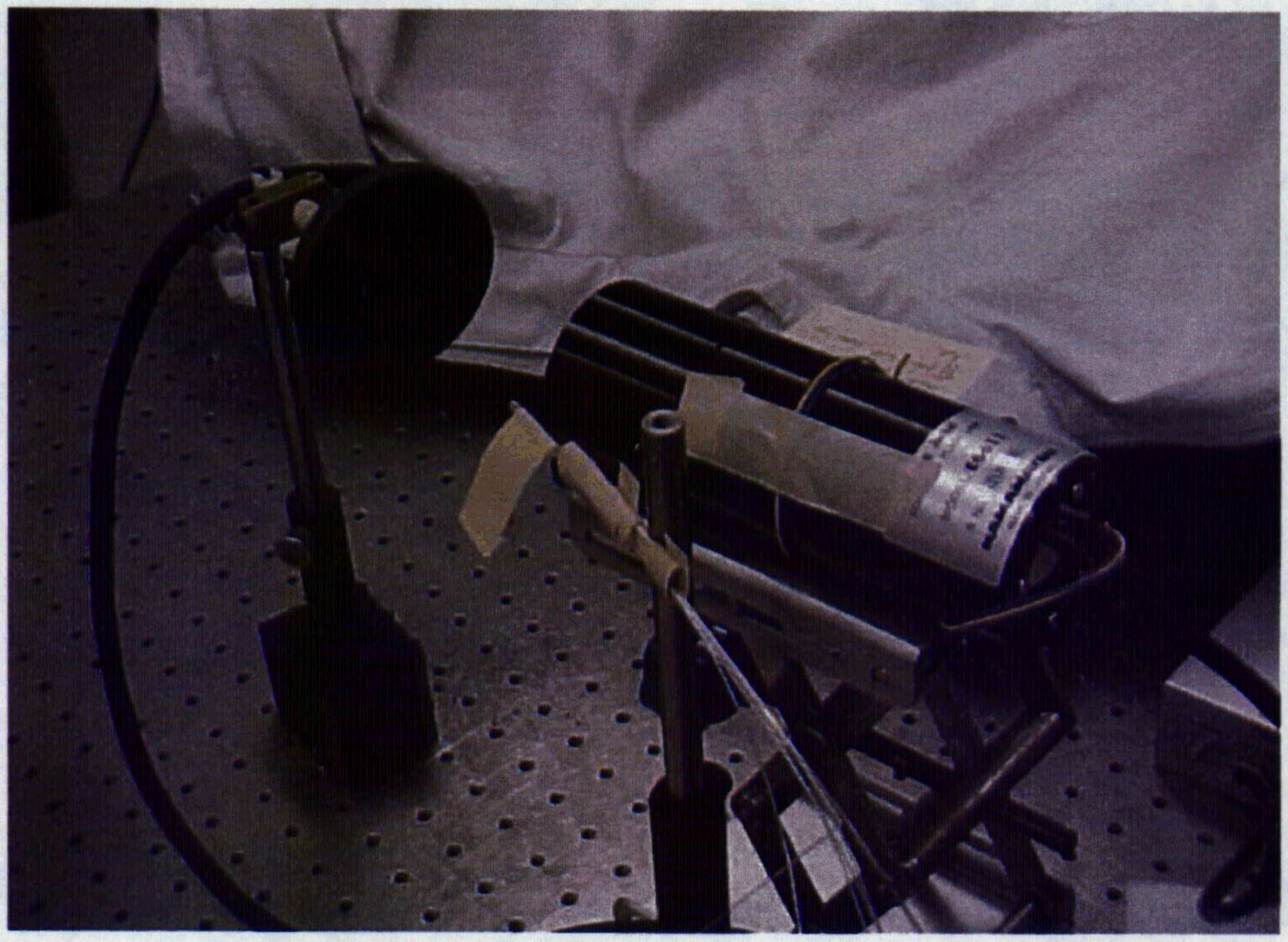

Fig. 1: The set-up of the Xe flash lamp, fiber optics, and hot surface.

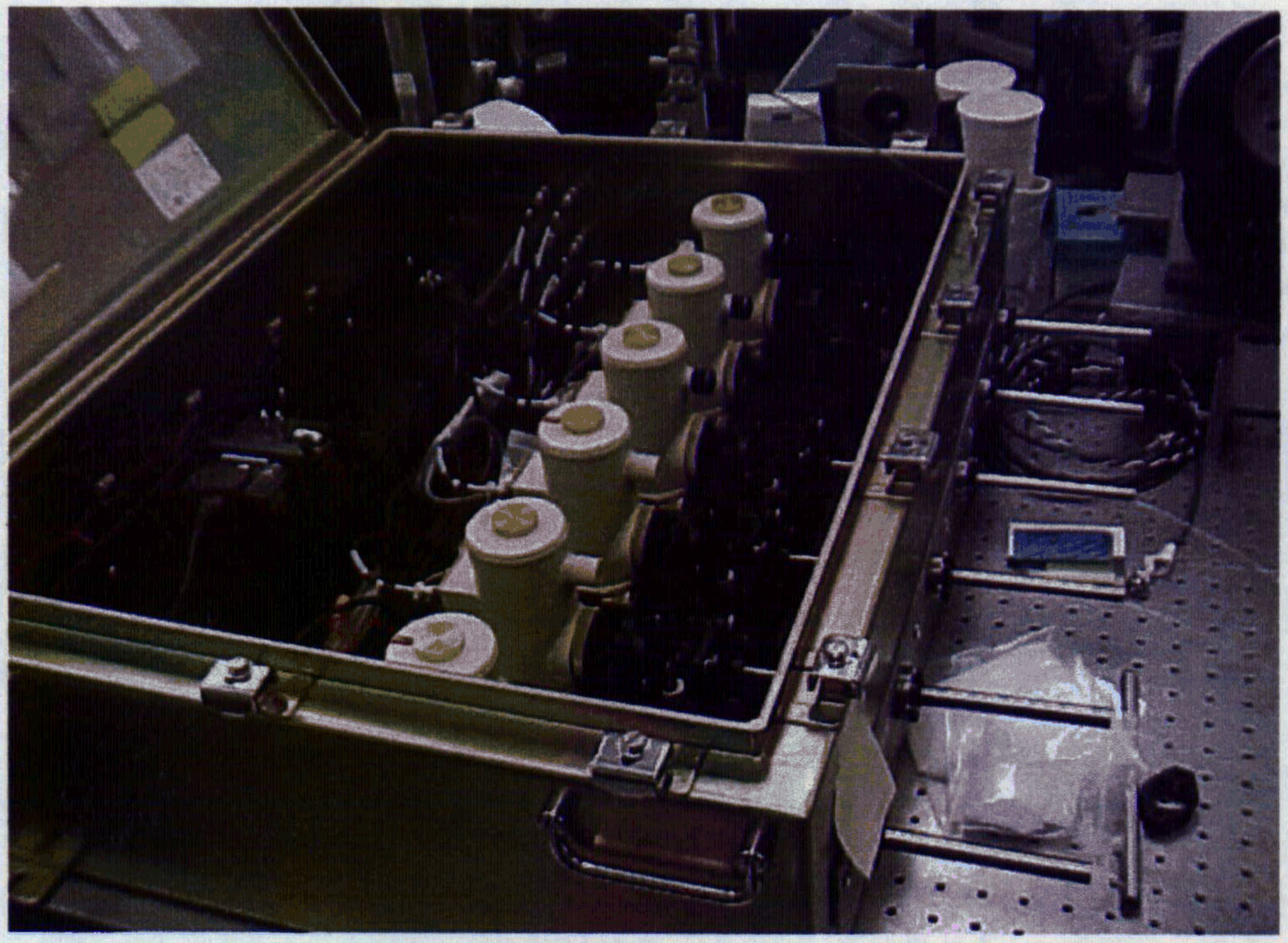

Fig. 2: The detectors and the optical coupling (including filters) to the fiber optics.

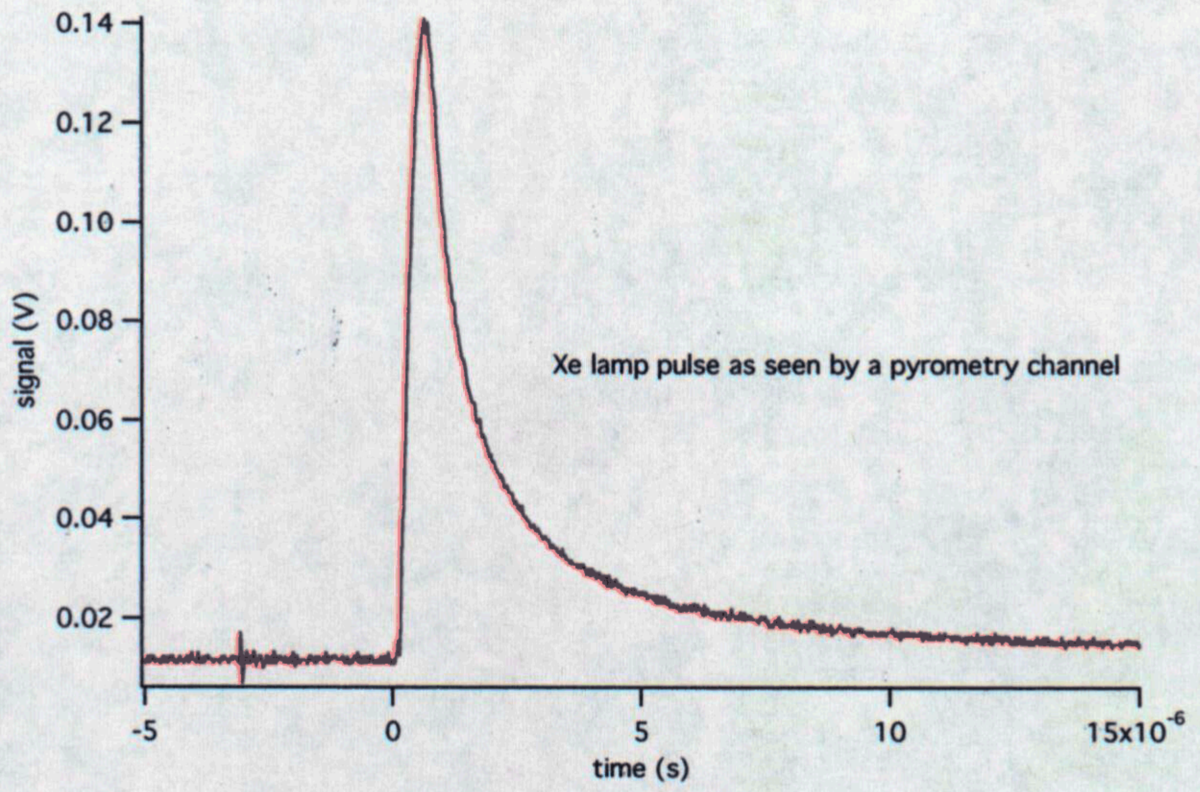

Fig. 3: The Xe lamp pulse signal as recorded in one of the pyrometer channels.

Data is acquired in the following sequence. We first calibrate the detector using a blackbody source (from Infrared Systems Development Corp.). The relative values of the sensor calibration factors C_i are then computed from the signal strengths and the relation for black body power flux integrated over the bandpass for each channel. The spectrum of the Xe lamp is then measured to obtain the relative intensities in each channel, e.g. E_i. We then heated the warm surface and made measurements with a thermocouple and an IR thermopile (Wahl Heat Spy Infrared Thermometer). Knowing the temperature from the thermocouple, the thermopile allowed an estimation of emissivity as a function of temperature (see Fig. 4). The signal due to the emitted light was measured by the pyrometer at an angle of approximately 10 degrees from the normal allowing the computation of the values of A_i. We then measured the specular reflection of the light from the pulsed Xe lamp at the same angle and obtained the values of D_i.

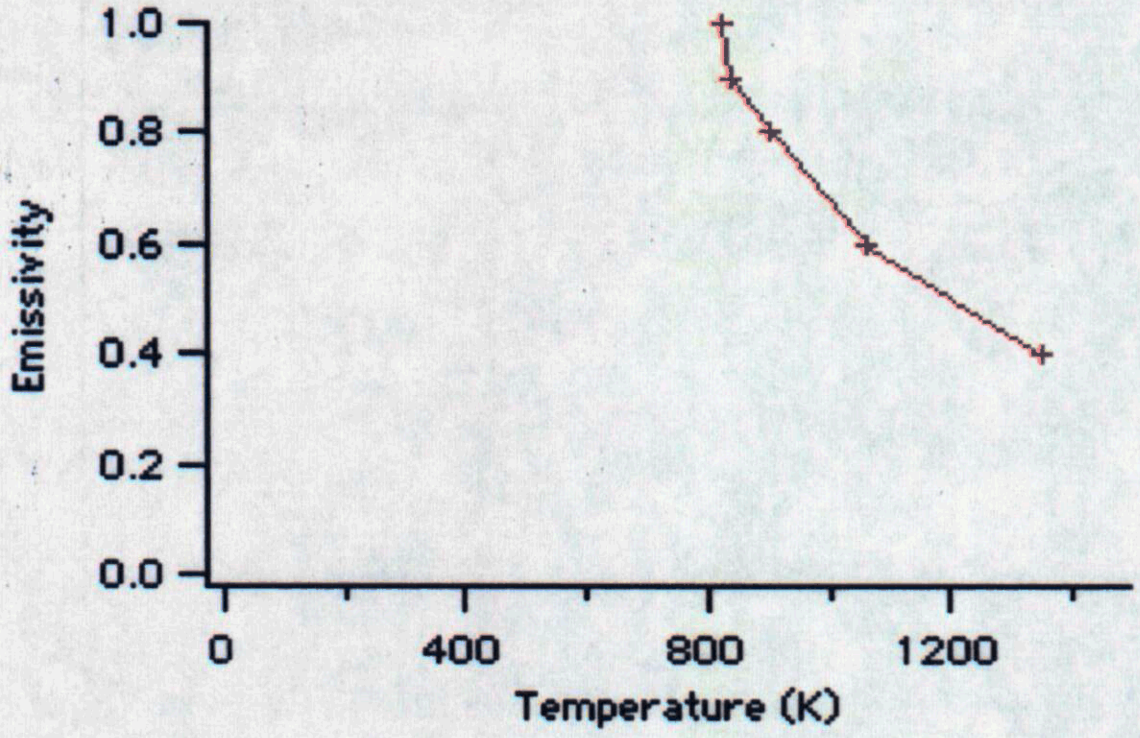

Fig. 4: Temperature vs. emissivity using the Wahl thermopile pyrometer and thermocouple.

The data for the experiment is shown below in Table 1. We only used 4 channels corresponding to center wavelengths of 1.64, 2.25, 3, and 4 m. At these low temperatures, there is not enough emitted signal at smaller wavelengths, and we can t get a reflected signal beyond 5 m due to the sapphire cut-off on the Xe lamp. We normalize against the 3μm channel.

Table 1: Data for Tabletop Experiment

Channel	Wavelength (μm)	C_i/C_n	A_i	D_i	E_i	R_i/R_n
2	1.64	0.524	0.04	1.03	1.09	0.9604
3	2.25	0.632	0.33	1.40	1.42	0.986
4	3	1	1.00	1.00	1.00	1
5	4	0.327	1.70	1.18	0.94	1.2529

Fig. 5 is a plot of the equations discussed above. The intersections of the lines are solution points. The computed temperatures are 840 K and 850 K with channel 4 emissivities of 0.63 and 0.65, respectively. Using the greybody method, the calculated temperatures are 850, 860, and 960 degrees Kelvin, depending on which pair of channels was used. The thermocouple measurement of the surface yielded 840 degrees Kelvin.

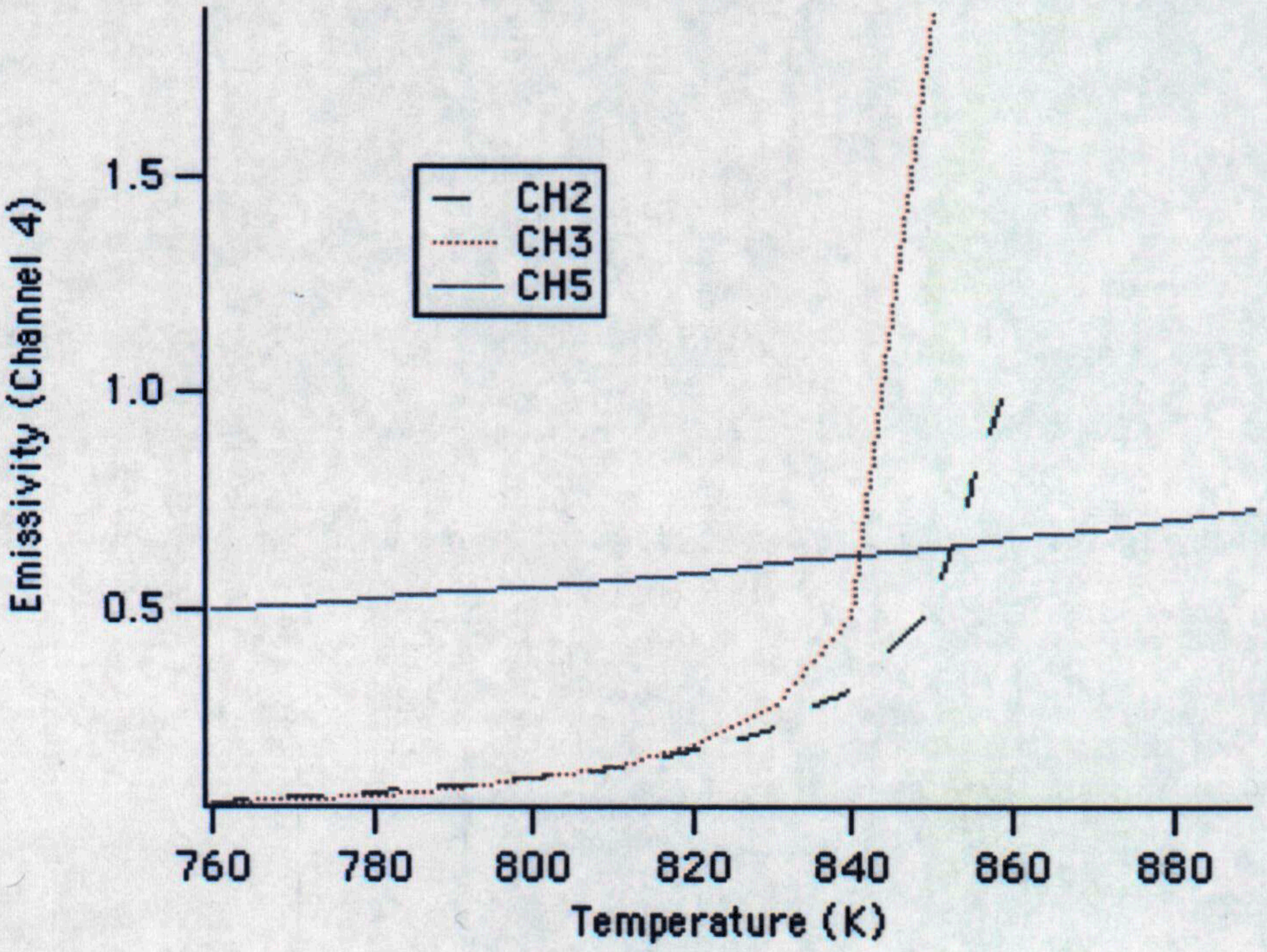

Fig. 5: A plot of emissivity in Channel 4 vs. temperature for the other channels. The intersection of the lines represents the solution point for the set of equations

The calculated emissivities for the Mo surface at a temperature of 840 degrees Kelvin are 0.70 for channel 2, 0.64 for channel 3, 0.63 for channel 4, and 0.53 for channel 5. For a temperature of 850 K, the emissivities are 0.68 (ch2), 0.65 (ch3), 0.65 (ch4), 0.56 (ch5). If the temperature of the surface is 840 degrees Kelvin, the Wahl pyrometer indicates an average emissivity of 0.9.

We substituted a Au surface for the Mo to compute the emissivity by comparing the reflected signal from the Au with that from the Mo and obtained an emissivity of approximately 0.95 in all channels. From the gray body results, which gave temperatures of 850, 860, and 960, it is evident that the emissivities are not equal in all channels, and that in particular the emissivity in Channel 5 is different from the others. Hence the reflectivity experiment didn t give the emissivities. The primary reason for this is believed to be due to the lack of integration of the reflectivities and emissivities over all angles.

The emissivities we calculate range from 0.53 to 0.70 and are significantly different from the value of 0.90 average that we obtained from the combination of the thermocouple and the pyrometer. Some part of this difference is again due to the lack of integration over space, and another due to the sensitivity of the equations and the errors in the data. Since the signals from the reflected light were relatively small, they were subject to error, and 0.5 mV changes in the 1.5 mV signal in Channel 5 (on the order of 0.5 mV) would bring the emissivities up to the 0.9 level without significantly changing the calculated temperature. The maximum variation in four sequential data sets for the reflectivity signal in channel 5 was 0.4 mV.

A fundamental problem with the tabletop system is that the Mo oxidizes at high temperatures so it was decided to pursue further developments in the dynamical system.

Gas Gun Experiments

Two experiments have been performed so far on a two-stage light gas gun. The target consisted of a 6mm thick mirror finish Mo plate to which a 15 mm thick LiF window was bonded with UV curable glue (Loctite 352). The non-Mo-contacted surfaces of the LiF were gold-coated (about 200 nm) to form the signal-integrator cavity, except for a small uncoated area center and directly opposite the Mo, just large enough to allow the fiber bundle of the IR detector access to the integrator interior. We used copper impactors at a nominal velocity of 2.6 km/s. From calculations, we expect a temperature of roughly 800 K, a peak pressure of 78 GPa and release at the LiF window to 34 GPa.

Fig. 6 shows the output from 4 channels for Shot 3647. Notice that the voltage plateau is on the order on 3/4 μs.

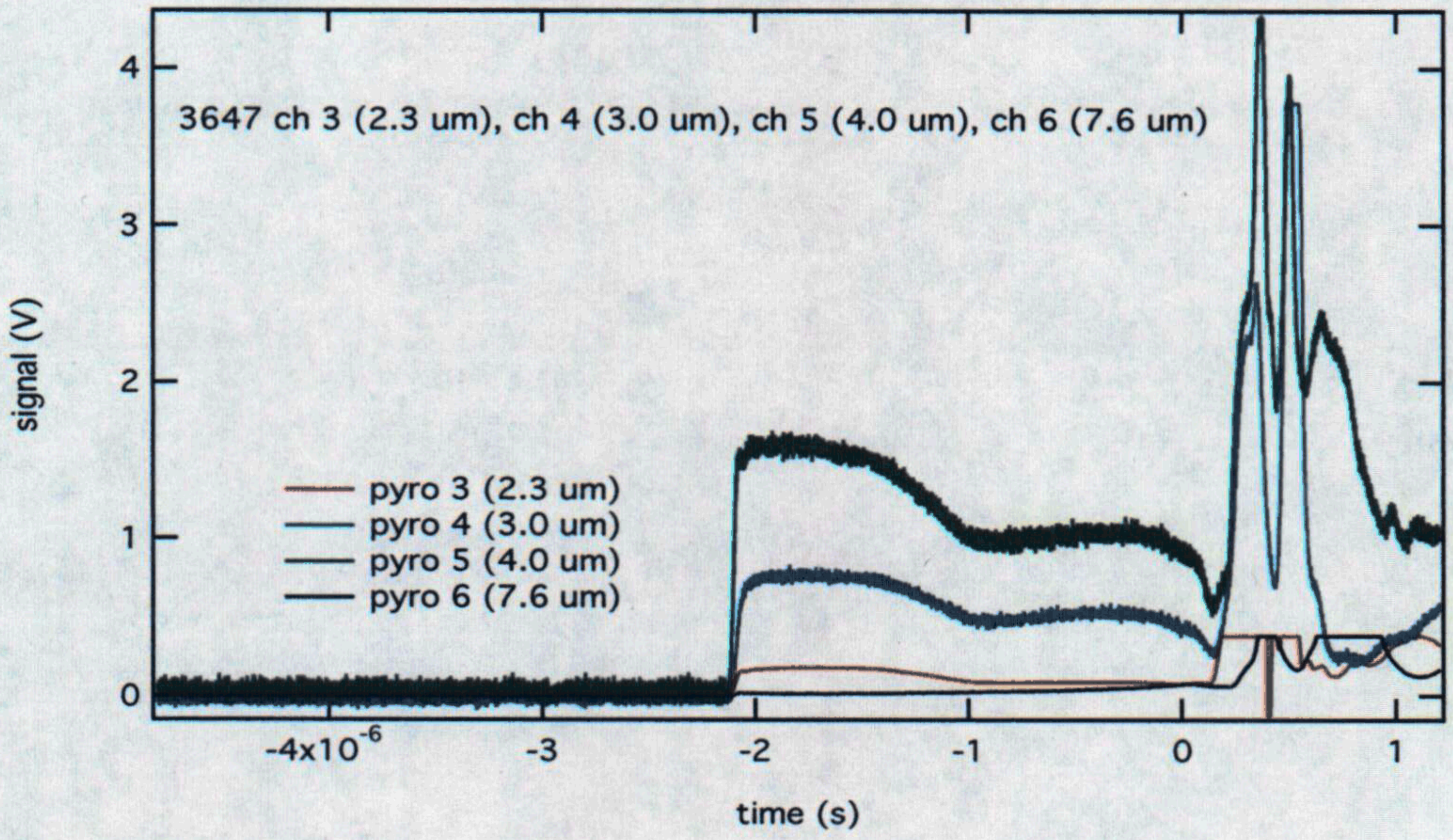

Fig. 6: Voltage vs. Time for the IR-Detector in Shot 3647.

In this shot, the Xe lamp did not trigger so that no reflectivity data was acquired. A greybody analysis was performed on the data, but did not give a consistent temperature. While other factors cannot be disregarded, this is consistent with a wavelength dependent emissivity.

Fig. 7 shows the data for Shot 3648. These data show the sum of the emitted and reflected power of the light in the wavelength intervals associated with each channel. The signals are given as a function of time and the beginning of the non-zero signal corresponds to the signal from the emitted light from the shocked material. The Xe lamp fired a few hundred nanoseconds after the initial appearance of light from the shocked surface.

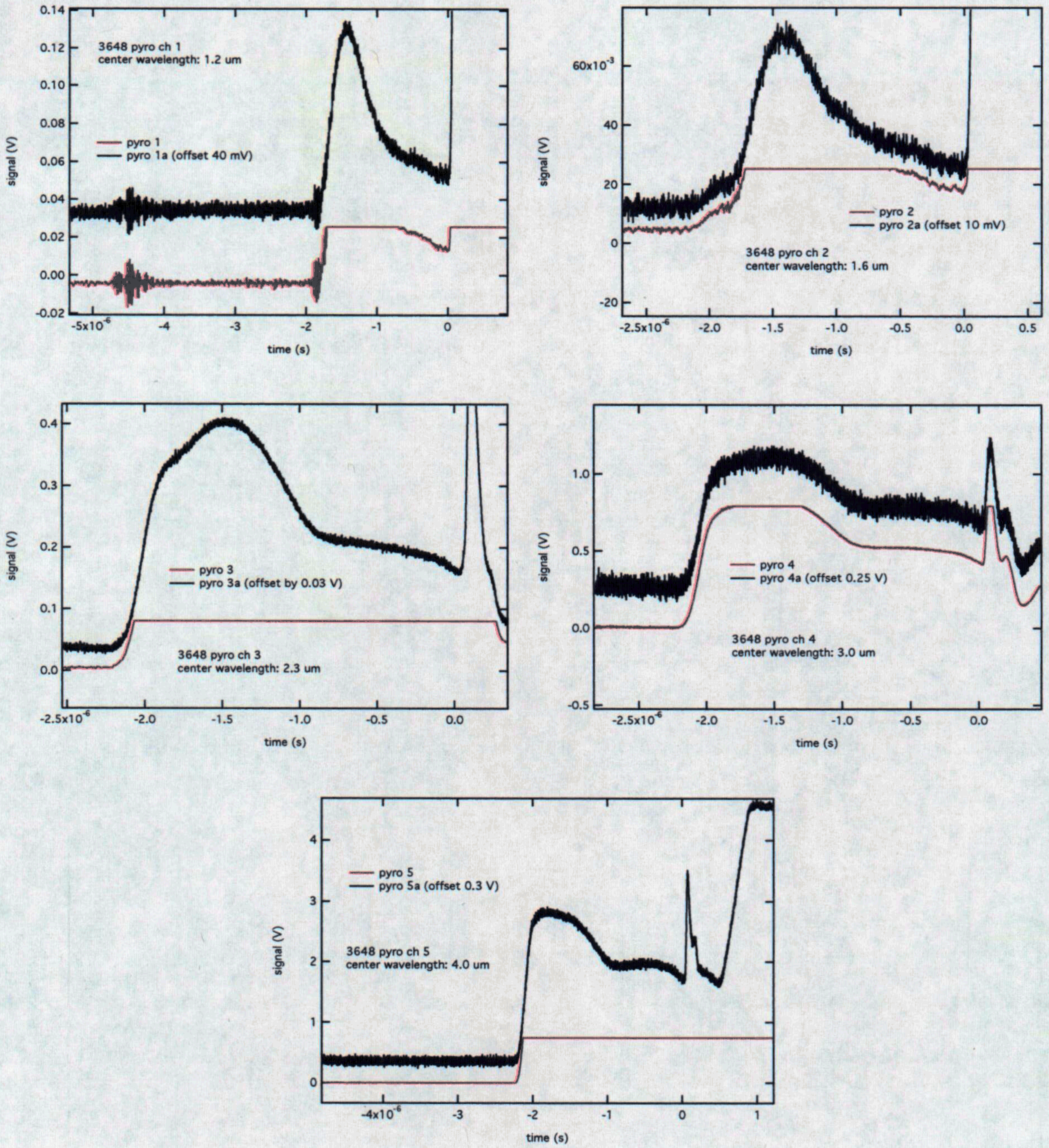

Fig. 7: Voltage vs. Time for the IR-Detector in Shot 3648.

In channels one and two the reflected light from the Xe source dominates the measurement although the signals from the emitted light can be distinguished from the reflected light in channel two. In the longer wavelength channels the signal from the reflected light dominates. Since the analysis requires that the magnitude from both the emitted and the reflected light to be measured in each channel, it is important that the signal from the emitted light reaches a steady state value prior to the onset of the reflected light. In this experiment the timing of the reflected light was slightly off so this condition was not met. In addition, it is useful for the purposes of accurate data acquisition that the power of the emitted and reflected light is of the same order of magnitude. Hence in future experiments we will decrease the strength of the xenon source in the wavelength range corresponding to channels one and two, and increase the strength in the longer wavelength channels.

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References

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